Extra Solar Planets
Origin and Nature of Planetary Systems

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Introduction: While there is only one Solar System (the system of the star Sol), as of early May 2019, there are over 3,025 known extrasolar planetary systems with more than 4,050 known and confirmed planets (called extrasolar planets or exoplanets). Of these planetary systems 658 have two or more planets. Over 150 exoplanets are in stars systems with two or more stars. They may orbit both stars (just like Tatooine in Star Wars) or orbit one star in a multi-star system. There are also two known (confirmed) planets that do not orbit a star—orphan planets. In this activity, we will construct models of eight of these planetary systems and compare them with our Solar System.

Scale Modeling: Size and distance scales in the Solar System and beyond are difficult to create without introducing misconceptions. When demonstrating phases of the Moon, for example, it is difficult to model simultaneously both the *sizes* of the Earth and Moon as well as their *distances*. The same is true for the modeling the sizes of the planets and their distances from the Sun, as well as the distances to the stars we see in the night sky and their planetary systems. Because of limited time and space, we, as a group, will model the Earth/Moon system, the relative sizes of the planets in our Solar System, the distance scale of our Solar System and several other planetary systems, and the distances to those systems.

Materials: We have Play-Doh© and plastic balls to model the Earth/Moon system (size and distance, respectively). We have laid out balls and beads to represent the planets of the Solar System. We have laid out macramé strings and twine to represent the solar distances of the planets of our Solar System (plus Pluto) and the distances of the eight other planetary systems listed below. The scale for these planetary system models is 1 meter = 100,000,000 kilometers, so the distance from the Sun to the Earth (149,600,000 kilometers = 1 Astronomical Unit [AU]) is 1.5 meters in this model. On this scale, the diameter of the Sun is about 1.4 cm and the Earth 0.13 mm. All of the models include scale-model-sized beads that also represent the colors of the stars, themselves. The planets are much too small to be seen on this scale. Because the distances are so great, the scale distance used for the string models for HR 8799 and Fomalhaut is 1 meter = 1,000,000,000 kilometers in order to conserve string. **Note: As with any model the sizes and distances are approximate, limited by the sizes of available beads, etc.**

Activities:

- The Play-Doh© has been divided in 50 equal balls. If you were to make a scale model of the relative sizes of Earth and Moon using all of these balls, how many would be needed for the Earth and how many for the Moon? To represent accurately the distances between them, how far apart would you need to put the Moon from the Earth (answers on page 3)?
- We now have a set of balls and beads that represent the planets (plus Pluto). On this scale, the Sun would be a little less than 5 feet in diameter (4.6 feet or 139 cm). On this scale, how far would Mercury be from the Sun (answer on page 3)?
- Using Table 1 below, we have created a scale model of our Solar System and eight extrasolar planetary systems. Do any of them look like our Solar System? How are they similar and different?
- We have included a model for another system, Jupiter and its four largest moons. For the string model, we used the same scale as the previous systems, 1 meter = 100,000,000 kilometers. However, we have also enlarged the model to 1 meter = 10,000,000 kilometers so that we can show the smaller bodies to scale. This was the first "planetary" system to be observed through a telescope. When Galileo first observed them in 1610, he called them planets. They are, in fact, larger than all of the dwarf planets and Ganymede is larger than Mercury.

- Table 2 gives the distances of the stars from the Solar System in light-years (ly). Given that one light-year, the distance light travels in a year, equals 9.46 x 10^{12} kilometers or 63,241 AU, create a scale that would represent the distances to the seven planetary systems from the Solar System. How big, in your scale model, would the individual planetary systems be?

Discussion: How do these eight planetary systems compare to our Solar System? Because of the methods used to discover these systems, two have lower limits for their planet masses and no information about their radii. Why? Several other planets have upper limits on their masses. Why? Do you notice any patterns in the distances of the planets from their respective stars? Their masses?

Table 1

Star	Distance (Light-years)	Planet	Dist. (AU)	Ang. Sep. Arcsec*	Model Dist (m)**	Period (Days/ Years)	Mass (E or J) ***	Radius (E or J)	Ecc.	Inc. ****
Sun	0.0	Mercury	0.39		0.58	88.0d	0.055 M_E	0.38 R_E	0.21	7.0°
		Venus	0.72		1.08	224.7d	0.82 M_E	0.95 R_E	0.009	3.4°
		Earth	1.00		1.50	365.3d	1.0 M_E	1.0 R_E	0.017	0.0°
		Mars	1.52		2.28	687.0d	0.107 M_E	0.53 R_E	0.093	1.9°
		Jupiter	5.20		7.79	11.86y	1.0 M_J, 317.8 M_E	10.9 R_E, 1.0 R_J	0.049	1.3°
		Saturn	9.58		14.3	29.46y	0.30 M_J, 95.2 M_E	9.0 R_E, 0.83 R_J	0.056	2.5°
		Uranus	19.2		28.8	84.32y	0.046 M, 14.5 M_E	4.0 R_E, 0.37 R_J	0.044	0.8°
		Neptune	30.1		45.0	164.79y	0.054 M_J, 17.1 M_E	3.9 R_E, 0.36 R_J	0.011	1.8°
		Pluto	39.3		58.7	248.04y	0.0022 M_E	0.18 R_E	0.245	17.2°
HR 8799	129	e	14.5	0.37	21.8	49.3y	5-13 M_J			
(Imaged)		d	27	0.68	41	113y	7-13 M_J	1.2 R_J		28°
		c	43	1.09	65	225y	7-13 M_J	1.3 R_J		28°
		b	68	1.73	102	450y	5-11 M_J	1.1 R_J		28°
Fomalhaut A	25.1	b	115	15	172	880y	0.05−1 M_J		~0.1	66°
(Imaged)										
55 Cancri A	40.2	e	0.016	0.0013	0.024	0.74d	~0.027 M_J, ~7.8 M_E	2 R_E	0.17	83°
(radial vel.)		b	0.11	0.0093	0.16	14.6d	~0.8 M_J		0.016	85°
		c	0.24	0.019	0.36	44.3d	≥0.17 M_J		0.09	
		f	0.78	0.063	1.17	261d	≥0.14 M_J		0.000	
		d	5.76	0.47	8.63	14y	≥3.8 M_J (4.8 M_J?)		0.025	53°?
Upsilon Andromedae A	44.0	b	0.06	0.004	0.09	4.62d	0.69 M_J		0.013	30°
		c	0.86	0.064	1.24	238d	14.6 M_J		0.24	8°
(radial vel.)		d	2.55	0.19	3.8	3.57y	10.2 M_J		0.27	24°
		e	5.25	0.39	7.9	10.5y	1.1 M_J		0.005	
Kepler-11	2,000	b	0.091		0.14	10.3d	4.3 M_E	1.97 R_E		88.5°
(transit)		c	0.106		0.16	13.0d	13.5 M_E	3.15 R_E		89°
		d	0.159		0.24	22.7d	6.1 M_E	3.43 R_E		89.3°
		e	0.194		0.29	32.0d	8.4 M_E	4.52 R_E		88.8°
		f	0.25		0.38	46.7d	2.3 M_E	2.61 R_E		89.4°
		g	0.462		0.69	118.4d	<300 M_E	3.66 R_E		89.8°
Kepler-16 AB	196	b	0.705	0.01	1.05	228.8d	0.33 M_J	0.75 R_J	0.007	90.0°
(transit)										
Kepler-20	950	b	0.045	0.0002	0.068	3.70d	8.7 M_E	1.91 R_E	<0.32	86.5°
(transit)		e	0.051	0.0002	0.077	6.10d	0.39−1.67 M_E	0.87 R_E	<0.28	87.5°
		c	0.093	0.0004	0.14	10.9d	16.1 M_E	3.07 R_E	<0.40	88.4°
		f	0.11	0.0004	0.17	19.6d	0.66−3.04 M_E	1.03 R_E	<0.32	88.7°
		d	0.35	0.0012	0.52	77.6d	<20.1 M_E	42.75 R_E	<0.60	89.6°
Kepler-42	125	c	0.006	0.0002	0.009	0.45d	<2.1 M_E	0.73 R_E		
(transit)		b	0.012	0.0003	0.018	1.21d	<2.7 M_E	0.78 R_E		
		d	0.015	0.0004	0.023	1.86d	<0.9 M_E	0.57 R_E		

Table 1 (Cont.)

Star	Distance (Light-years)	Planet	Dist. (AU)	Ang. Sep. Arcsec*	Model Dist (m)**	Period (Days/ Years)	Mass (E or J) ***	Radius (E or J)	Ecc.	Inc. ****
TRAPPIST-**1**	39.5	b	0.011	0.018	0.017	1.51 d	0.79 M_E	1.09 R_E	0.019	89.65°
		c	0.015	0.025	0.023	2.42d	1.63 M_E	1.06 R_E	0.014	89.67°
		d	0.021	0.035	0.032	4.05d	0.33 M_E	0.77 R_E	0.003	89.75°
		e	0.028	0.047	0.042	6.10d	0.24 M_E	0.92 R_E	0.007	89.86°
		f	0.037	0.062	0.056	9.21d	0.36 M_E	1.04 R_E	0.011	89.68°
		g	0.045	0.075	0.068	12.35d	0.566 M_E	1.13 R_E	0.003	89.71°
		h	0.060	0.100	0.090	18.77d	0.086 M_E	0.71 R_E	0.086	89.8°
Proxima Centauri (Alpha Centauri C) (Radial Velocity)	4.25	b	0.045	0.7	0.068	11.19d	1.27 M_E	1.27 R_E	<0.35	
	Distance (AU)	**Moon**	**Dist. (AU)**	**Ang. Sep. Arcsec***	**Model Dist (m)****	**Period (Days/ Years)**	**Mass (E or J) *****	**Radius (E or J)**	**Ecc.**	**Inc. *******
Jupiter System	5.2	Io	0.003	139.	0.004	1.77d	0.01 M_E	0.28 R_E	0.004	87°
(Imaged)		Europa	0.004	220.	0.007	3.55d	0.008 M_E	0.25 R_E	0.009	87°
		Ganymede	0.007	351.	0.011	7.16d	0.02 M_E	0.41 R_E	0.001	87°
		Callisto	0.013	617.	0.018	16.7d	0.02 M_E	0.38 R_E	0.007	87°

*As viewed from Earth. An arcsecond is an angular measurement equal to 1/60 of an arcminute and 1/3600 of a degree. Since the Moon is about one-half of a degree (30 arcminutes), an arcsecond is 1/1800 the width of the Moon. From 3.26 ly away, the Earth would have a maximum separation of 1 arcsecond from the Sun.
**One meter = 100,000,000 km
***For radial velocity measurements, mass is related to the inclination of the orbit (as viewed from Earth); however, since the inclinations of the orbits cannot be measured with this method, the masses are minimum masses.
****For exoplanets, the inclination is defined by the orbit's angle as viewed from Earth: 0°, pole on; 90°, edge on. For transits, the exoplanet orbits must be viewed nearly edge-on. For radial velocity measurements, an assumption of edge-on gives the minimum possible mass.

Note: The stars in three of the planetary systems have an A or B after the star names. This implies that these are multiple star systems. In two cases Fomalhaut, and Upsilon Andromedae, the planets orbit the primary star and the other stars are much farther away. There are three stars in the Fomalhaut system and two in the Upsilon Andromedae system. Kepler 16 is a close binary system with the planet orbiting both stars.

Table 2: Information about the stars

Star	Distance (Light-Years)	Model Dist. (km)*	Mass (Relative to Sun)	Diameter (Relative to Sun)	Spectral Type	Temperature	Luminosity (Relative to Sun)	Age (Billion Years)
Sun	0.000016	0.0015	1.00	1.00	G2	5,778 K	1.0	4.6
HR 8799	129	12,000	1.47	1.34	A5	7,430 K	4.9	0.06
Fomalhaut A	25.1	2,380	1.92	1.84	A3	8.590 K	16.6	0.44
55 Cancri A	40.2	3,800	0.95	1.15	K0	5,370 K	0.63	10
Upsilon Andromedae A	44.3	4,200	1.28	1.28	F8	8,070 K	3.6	2.6
Kepler-11	2000	189,000	0.95	1.10	G8	5,700 K	~1.1	8
Kepler-16 A Kepler-16 B	196	19,000	0.69 0.20	0.65 0.23	K M	4,450 K 3,000 K?	~0.15 ~0.004	?
Kepler-20	950	90,000	0.91	0.94	G8	5,470 K	~0.8	9
Kepler-42	125	12,000	0.13	0.17	M5	3,070 K	0.0024	?
Proxima Centauri	4.25	400	0.123	0.14	M6	3,040 K	0.0017	4.85
TRAPPIST-1	39.5	3,700	0.08	0.12	M8	2,550 K	0.0005	0.5-1.0

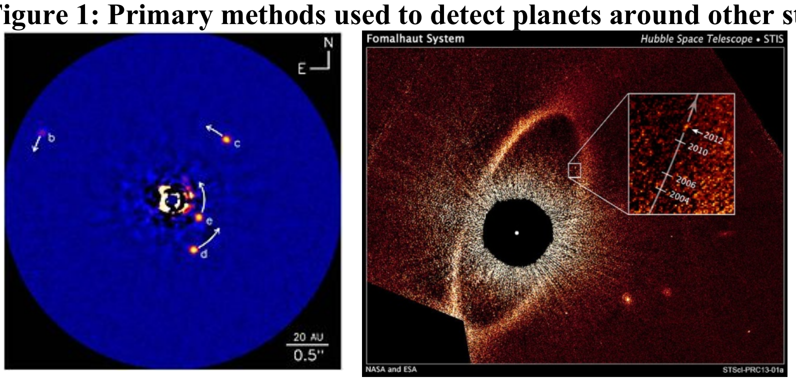
*One meter = 100,000,000 km

Recently, the International Astronomical Union held an exoplanet naming contest. People around the world were able to vote to name 31 exoplanets and the stars they orbit. Of the 19 stars that these exoplanets orbit, 5 already had formal names: Ain, Edasich, Errai, Fomalhaut, and Pollux, so only 14 stars have official new names. The names that relate to the stars and exoplanets in this activity are given in Table 3.

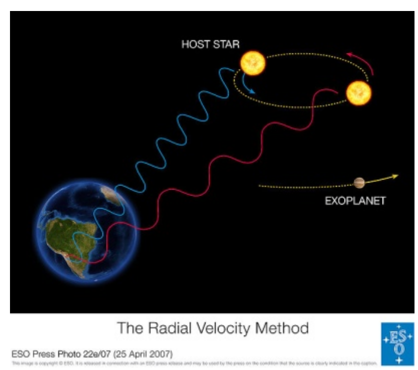
Table 3: New Star and Planet Names

Star Name	New Star Name	Exoplanet Designation	New Exoplanet Name
Fomalhaut	Fomalhaut	Fomalhaut b	Dagon
55 Cancri	Copernicus	55 Cancri b	Galileo
		55 Cancri c	Brahe
		55 Cancri d	Lipperhey
		55 Cancri e	Janssen
		55 Cancri f	Harriot
Upsilon Andromedae	Titawin	Upsilon Andromedae b	Saffar
		Upsilon Andromedae c	Samh
		Upsilon Andromedae d	Majriti
		Upsilon Andromedae e	

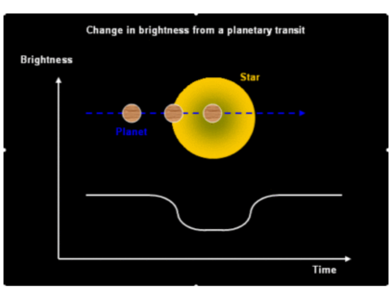
Figure 1: Primary methods used to detect planets around other stars



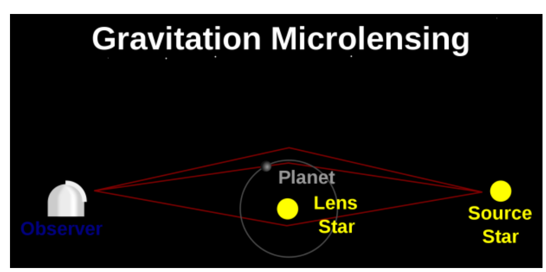
Imaging (HR 8799 and Fomalhaut)



Radial Velocity
(55 Cancri and Upsilon And.)



Transit (Kepler-11, 20, and 42)



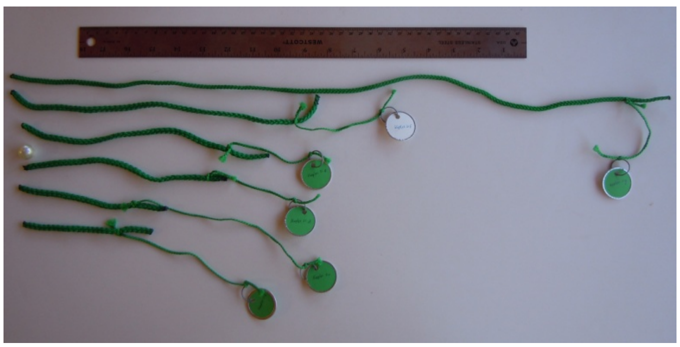
Microlensing (not represented in activity)

Eighteen exoplanets have also been discovered by pulsar and variable star timing and by the eclipse timing of other exoplanets.

Answers to activity questions:

1. Given 50 equal-sized clay balls, you would need 49 to represent the Earth and 1 to represent the Moon. To represent the distance from the Earth to the Moon, you would have to put the Moon at a distance equal to 30 times the diameter of the Earth (the diameter of Earth is 3.67 times the diameter of the Moon, so the Earth-Moon distance would also be 110 times the diameter of the Moon). The Earth-Moon distance is represented by the string of plastic balls.
2. This scale is 1 meter = 1 million kilometers, so Mercury would be 58 meters away from the Sun (mean distance). You need this scale, relative to the distance scale, in order to be able to see the relative sizes of the planets.
3. Jupiter and its four Galilean moons!

Figure 2: Examples of exoplanet systems


Model of Kepler 11 and its exoplanets (distances)

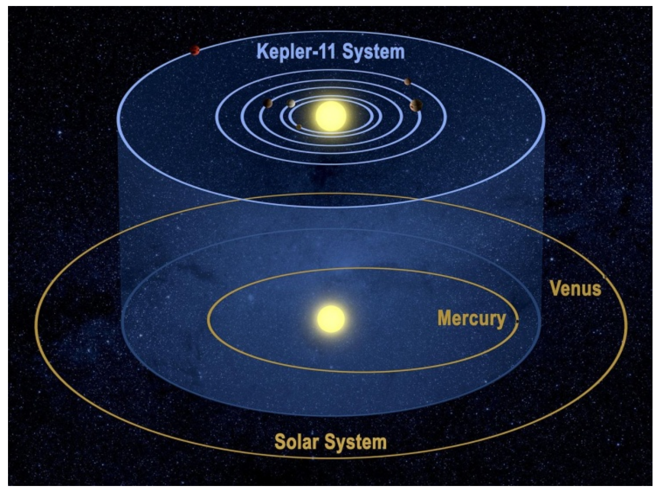
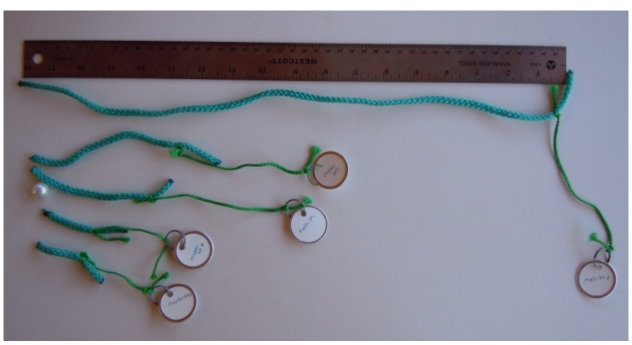


Illustration of the Kepler 11 system: Wikipedia


Model of Kepler 20 and its exoplanets (distances)

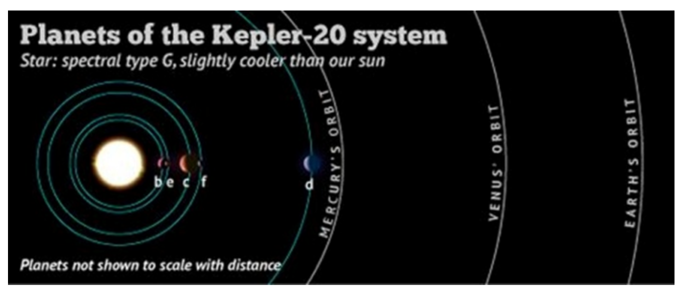


Illustration of the Kepler 20 system: Space.com

Setting up the string model of the
55 Cancri system (right)

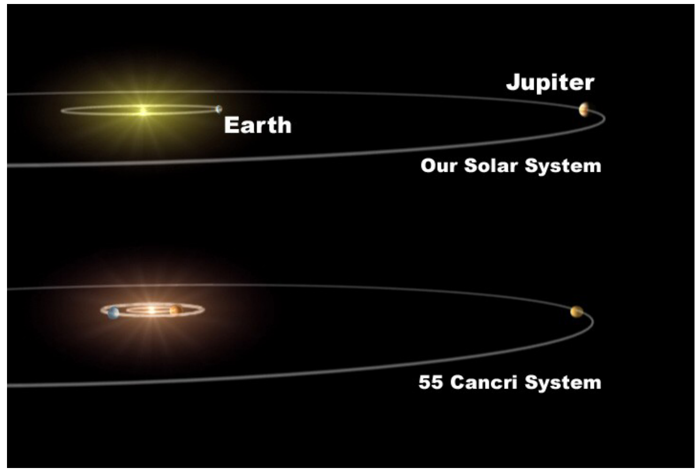


Illustration of the 55 Cancri system: Wikipedia